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LA-UR--82-1054

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TITLE: LONG TITANIUM HEAT PIPES FOR HIGH-TEMPERATURE SPACE RADIATORS

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SUBMITTED TO: 17th Intersociety Energy Conversion Engineering Conference
August 8-13, 1982
Los Angeles, California

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LONG TITANIUM HEAT PIPES FOR HIGH TEMPERATURE SPACE RADIATOR*

by

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ABSTRACT

Titanium heat pipes are being developed to provide light weight, reliable heat rejection devices as an alternate radiator design for the Space Reactor Power System (SP-100). The radiator design includes 360 heat pipes, each of which is 5.2 m long and dissipates 3 kW of power at 775 K. The radiator heat pipes use potassium as the working fluid, have two screen arteries for fluid return, a roughened surface distributive wicking system, and a D-shaped cross-section container configuration. A prototype titanium heat pipe, 5.5-m long, has been fabricated and tested in space-simulating conditions. Results from startup and isothermal operation tests are presented. These results are also compared to theoretical performance predictions that were used to design the heat pipe initially.

BACKGROUND

The SP-100 space nuclear power system is being designed to produce 100 kW of electrical power for seven years and to be fully compatible for safe launch into low-Earth orbit by the Space Transportation System (STS). The power plant configuration shown in Fig. 1 has four major subassemblies: an enriched uranium-oxide fueled reactor cooled by 90 sodium-filled molybdenum heat pipes; a lithium-hydride shield that protects other parts of the space-craft from reactor radiation; silicon-germanium thermoelectric converters that produce electricity from the reactor supplied thermal energy; and a titanium heat pipe radiator that rejects waste heat from the converter system into space.

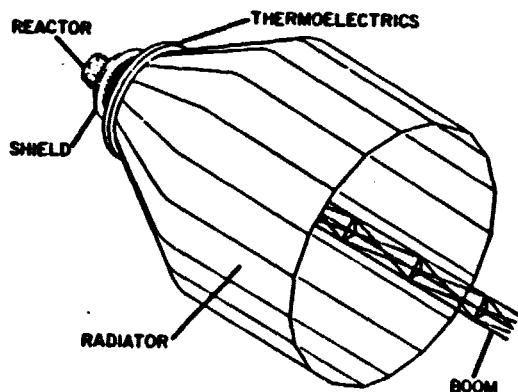


Fig. 1. Multiple panel heat-pipe radiator design.

The conical-cylindrical shaped radiator is segmented into thirty panels with each panel containing twelve radiator heat pipes as shown in Fig. 2. To obtain system redundancy, each core heat-pipe thermoelectric (TE) module package is in direct thermal contact with four radiator heat pipes through the TE module heat pipes. The exterior surface of the radiator panels is flat with the remaining portion of the individual heat-pipe containers being D-shaped. The D-shape was selected because it minimized radiator mass. Titanium was selected for the radiator material because of its relatively low density, ease of fabrication, good impact resistance and high-temperature capability. Table I lists size and mass data for a titanium radiator satisfying the 100 kW_e power system design criteria. Details of the radiator design are contained in Ref. 1.

HEAT PIPE DESIGN AND PREDICTED PERFORMANCE

The radiator heat pipes are designed to attain minimum mass while transporting the prescribed heat loads isothermally. The cross-sectional configuration of the titanium heat pipes varies from the view shown in the lower half of Fig. 3 at the smallest conical section radius to the view shown in the upper half of Fig. 3 at the cone/cylinder interface. The cross-sectional area available for vapor flow is

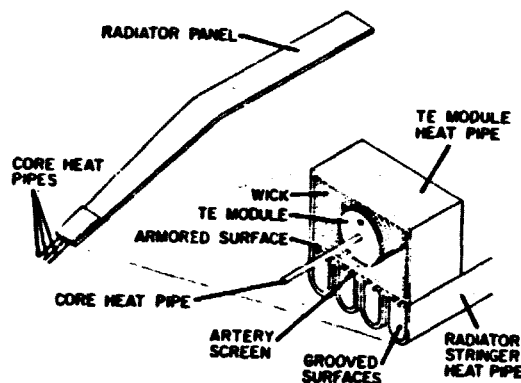


Fig. 2. Individual radiator heat-pipe panel.

TABLE I
TITANIUM RADIATOR CHARACTERISTICS FOR
100 kW_e POWER SYSTEM

Radiator power (kW)	1010
Total number of Ti/K heat pipes	360
Operating temperature (K)	775
Q _{max} /heat pipe (kW)	2.9
Heat pipe vapor area (mm ²)	582
Heat pipe length (m)	5.2
Radiator mass (kg)	384

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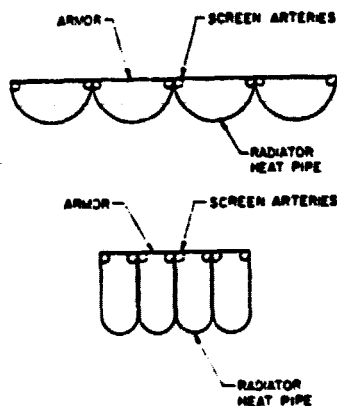


Fig. 3. Portion of a radiator heat-pipe panel segment.

constant along the entire length of the heat pipe and equal to 582 mm. The flat side radiates the waste heat to space. The TE modules are mounted on the flat side; both evaporation and condensation occur on this surface. Current designs assume a TE evaporator section 0.6 m long and a condenser 4.55 m in length. The resulting evaporator input heat flux is 24.4 W/cm²; the condenser heat flux is 1.8 W/cm².

The fluid wicking system uses arteries to transport potassium from the condenser to the evaporator and a distributive wick to transport the liquid to and from the arteries. Two single-layer 80-mesh titanium-screen arteries supply the liquid return mechanism. Design of the distributive wicking system is concentrating on nonscreen wicking surfaces that include steel shot-blasting, machined V-grooving, and pyramid-shaped embossing. These types of fluid distribution systems eliminate the need to insert and attach a separate screen mesh to the inside of the irregularly-shaped heat pipe and reduce heat pipe weight.

Performance predictions for heat pipes consisting of evaporator and condenser sections have been calculated with the aid of a Los Alamos developed computer code HPIPE.² Calculations are based on a laminar-flow model; using the two-dimensional Navier-Stokes equations; and include compressibility effects. The hydrodynamic model of the heat pipe is essentially a pressure balance on the recirculating flow of the working fluid.

Computer calculations were made, utilizing this model, to predict performance limits of the titanium/potassium heat pipes. Figure 4 is a plot of the maximum powers obtainable for different artery sizes. Since the screen pore size determines the capillary force that supports the liquid-vapor pressure difference in the heat pipe, finer mesh screens allow for higher performance. Presently, titanium screens are available in 50- and 80-mesh weaves. For the current heat pipe design, 80-mesh screen would provide a heat transport performance margin of 1.9. Selecting the artery radius at 2.3 mm would allow the heat pipe to maintain its design power even if one of the two arteries becomes inoperable. Figure 5 is a plot of maximum heat pipe power vs evaporator exit temperature. As is evident in both Figs. 4 and 5, the design heat-pipe power of 2.94 kW is well below the sonic

limit, thus indicating minimal axial-temperature variation. Also shown in Figs. 4 and 5 is that maximum screen-pipe performance is confined by the wicking limit (screen pore size dependence limit). Figure 6 illustrates the predicted axial-temperature variation for the radiator heat-pipe design. Calculations indicate a 4 K temperature drop in the evaporator and a temperature recovery of 3 K in the condenser section. Note that at all locations in the condenser, the operating temperature is above the radiator design temperature of 775 K.

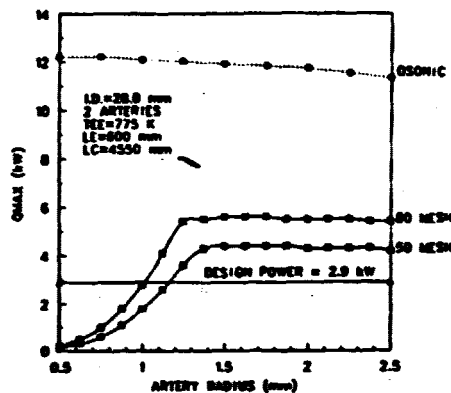


Fig. 4. Performance limits of radiator heat pipes with various screen meshes vs artery size.

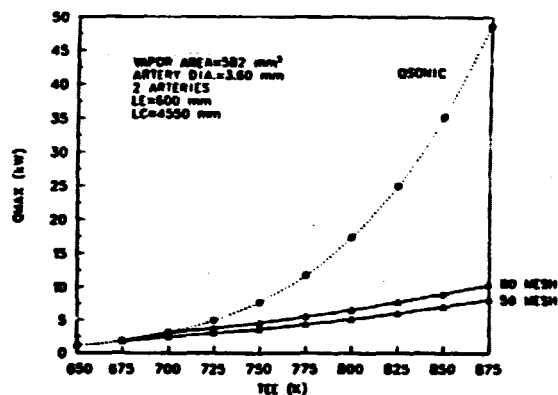


Fig. 5. Performance limits of radiator heat pipes vs temperature of evaporator exit.

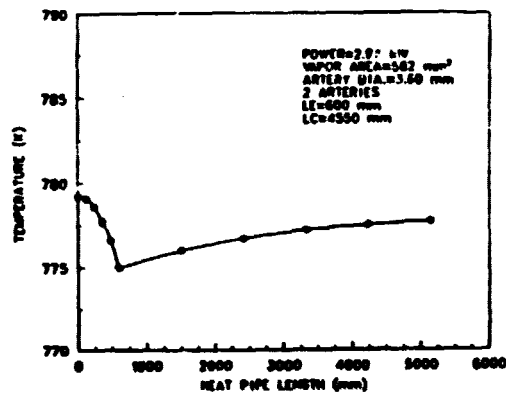


Fig. 6. Predicted axial-temperature variation of radiator heat pipes.

PROTOTYPE FABRICATION AND TESTING

Fabrication of prototype titanium heat pipes progressed in three stages from 0.3-m to 2-m to 5.5-m-long units. This sequence served the dual purpose of developing fabrication procedures while providing heat pipes for evaluation. The design features of a titanium heat pipe are shown in Fig. 7. Heat pipe components include the curved half-shell 0.56-mm thick, the flat top plate 0.56-mm thick, the two 50-mesh-Ti screen wick arteries, and two end caps with one containing the fill tube. These parts are fabricated separately and then welded together. The material used for the body of the heat pipe was Grade 2 Ti; the top plate and half-shell were fabricated from sheet stock, and the end caps were machined from plate. The single-layer screen arteries

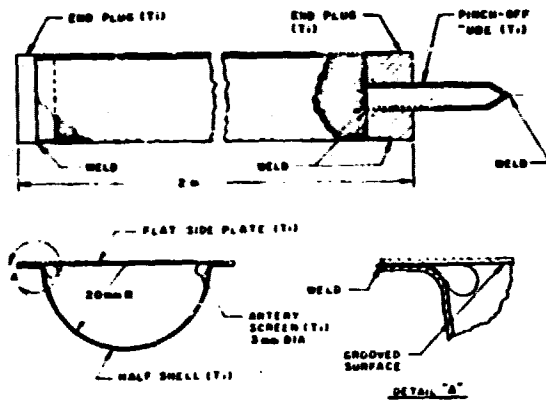


Fig. 7. Design features of a titanium heat pipe.

for the pipes were formed over a mandrel and then spot welded to the flat top plate before welding the flat and curved sections together in order to control artery dimension. The cross-sectional area available for vapor flow is 6.3 cm^2 while the arteries are each 12 mm^2 in cross section. The distributive wicking surface on the interior of all heat pipes was provided by steel shotblasting the titanium sheet prior to forming. Using the fill tube in one of the end caps, the heat pipe is evacuated and then enough potassium is added by vacuum distillation to fill the arteries and saturate the distribution wick. The 5.5-m heat pipe was filled with 260 g of potassium. After completion of the potassium transfer, the fill tube is weld sealed and the heat-pipe fabrication thereby finished.

Heat-pipe testing is performed under space-simulating conditions in a water-cooled vacuum chamber at 10^{-7} torr. Heat input to the evaporator was provided by rf heating in the 5.5-m heat pipe tests. Figure 8 shows the 5.5-m heat pipe instrumented and ready for assembly into the vacuum chamber.

Tests on the 5.5-m heat pipe were designed to obtain low power start-up characteristics and achievement of design power transport at an operating temperature of 775 K. The testing of high temperature performance limits was not possible due to the uncoated condition of the heat pipe (that is, a high-emissivity coating is required for radiative heat rejection at these higher powers). Figure 9 illustrates the variation in axial temperature profiles as power is increased during startup. The good correlation between analytical prediction and start-up power measurements in Fig. 10 indicates that the startup capability of the heat pipe is very stable and predictable in the low power range. As is evident in Fig. 11, data were obtained covering a wide operating

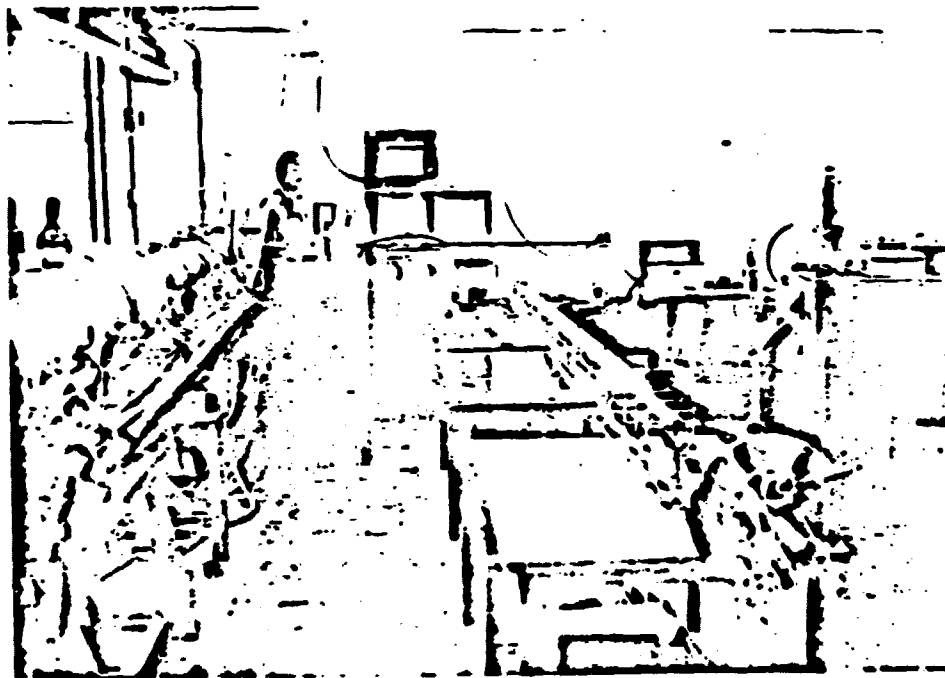


Fig. 8. Instrumented Ti/K heat pipe before assembly into vacuum tank.

temperature range of 180 K. The maximum heat pipe power attained was 1.86 kW at an average operating temperature of 760 K. This data point, 63% of design power, was a significant result since the heat pipe reached a heat input dry-out limitation. This limitation was a result of the shot-blasted distribution wick's inability to distribute enough working fluid for evaporation. This result thus indicates the necessity for wire screen supplementation in the evaporator section of the heat pipe to increase the fluid distribution capability. A comparison between the analytically predicted axial-temperature variation and the measured profile is shown in Fig. 12. The heat pipe was also operated successfully against

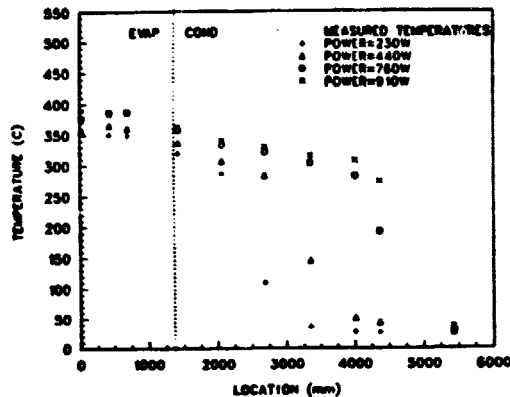


Fig. 9. Axial temperature profiles of 5.5-m Ti/K heat pipe during start-up.

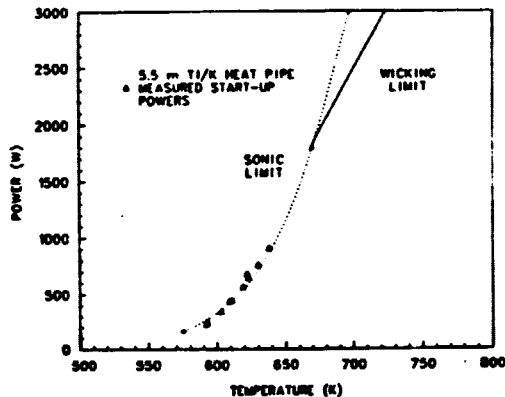


Fig. 10. Measured start-up powers of 5.5-m Ti/K heat pipe.

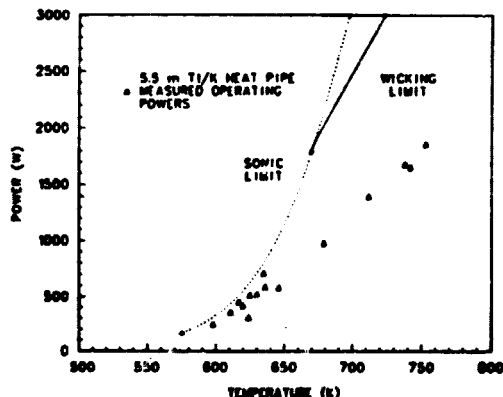


Fig. 11. Measured operating powers of 5.5-m Ti/K heat pipe.

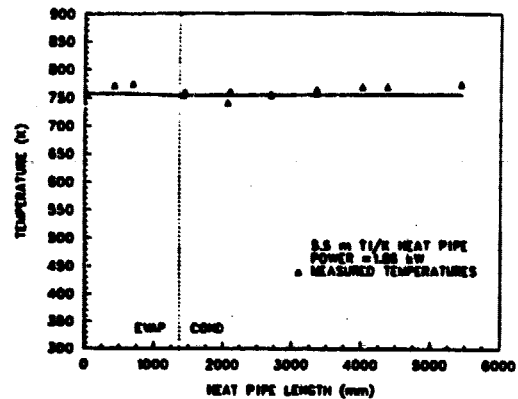


Fig. 12. Comparison of analytical and measured temperature profile at maximum operating power.

gravity (pipe tilted so that condenser section is lower than evaporator) thus demonstrating artery fill and operation.

SUMMARY

A dual artery titanium/potassium heat pipe, with a D-shaped cross-section, very lightweight structure and length of 5.5 m, has been constructed and tested in support of an alternate design for the SP-100 radiator subassembly. The successful design, fabrication, filling and testing of the 5.5-m heat pipe represents an important technological advance in the development of very long, light-weight, high-temperature heat pipes for space applications. Its length of 5.5 m makes it the longest alkali metal heat pipe ever tested. The fabrication and test of this heat pipe include the following significant accomplishments.

1. Successful completion of a major advance in heat pipe design, incorporating several design and fabrication procedures (thin sheet material, D-shaped cross-section and long axial welds) not previously demonstrated.
2. Successful filling and wet-in procedures developed for very long, thin-walled heat-pipe structures.
3. Stable start-up of very long arterial liquid-metal heat pipes demonstrated.
4. 1.86 kW of heat transported at 760 K demonstrating overall capability of the pipe.
5. Successful heat pipe operation against gravity demonstrating artery fill and operation.
6. Data indicating an input heat dry-out limit for the shot-blasted distribution wick showing the necessity for wire screen supplementation in the evaporator section.
7. Excellent correlation between analytical predicted performance and actual test data.

Further experiments on a similar heat-pipe design utilizing a wire screen for the evaporator distribution system and a high emissivity coating in the condenser would allow testing of heat pipe performance limits.

ACKNOWLEDGEMENTS

This work was performed jointly for the Advanced Nuclear Systems and Projects, Division of the U.S. Department of Energy and under subcontract 955935 for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NASA-100. The authors express their gratitude to James Sanz who contributed substantially to the assembly and operation of test facilities.

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